Period Doubling in *Kepler* RR Lyrae Stars

**R. Szabó, Z. Kolláth, L. Molnár, K. Kolenberg,
D.W. Kurtz, and WG#13 members**

Abstract The origin of the conspicuous amplitude and phase modulation of the RR Lyrae pulsation—known as the Blazhko effect—is still a mystery more than 100 years since its discovery. With the help of the *Kepler* space telescope we have revealed a new and unexpected phenomenon: period doubling in RR Lyr—the eponym and prototype of its class—as well as in other *Kepler* Blazhko RR Lyrae stars. We have found that period doubling is directly connected to the Blazhko modulation. Furthermore, with hydrodynamic model calculations we have succeeded in reproducing the period doubling and proved that the root cause of this effect is a high order resonance (9:2) between the fundamental mode and the ninth radial overtone, which is a strange mode. We discuss the implications of these recent findings on our understanding of the century-old Blazhko problem.

1 Period Doubling in Pulsating Variable Stars

Period doubling (PD) bifurcation is a well-known dynamical effect. In the parlance of dynamical systems a new limit cycle emerges from an existing limit cycle with a period twice as long as the old one. In the case of a pulsating star we observe

R. Szabó (✉) · Z. Kolláth · L. Molnár
Konkoly Observatory of the Hungarian Academy of Sciences, H-1121 Budapest,
Konkoly Thege Miklós út 15-17., Hungary
e-mail: rszabo@konkoly.hu

K. Kolenberg
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA,
Instituut voor Sterrenkunde, Celestijnenlaan 200D, 3001 Heverlee, Belgium

D. Kurtz
Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK

WG#13 members
http://astro.phys.au.dk/KASC/

Szabó, R. et al.: *Period Doubling in* Kepler *RR Lyrae Stars*. 81
Astrophys Space Sci Proc. **31**, 81–84 (2013)
DOI 10.1007/978-3-642-29630-7_16,

alternating cycles in the time domain. In the frequency domain PD manifests itself as half-integer frequencies (the f/2 subharmonic and its odd integer multiples). In stellar astrophysics the heyday of period doubling occurred more than two decades ago when it was discovered in one-dimensional hydrodynamic models of Cepheids [1,2,11] and Type II Cepheids [4,9] by J. R. Buchler and his collaborators. The cause of PD was found to be a low-order resonance between the fundamental mode and a low radial overtone. In the hydrodynamic model calculations mentioned above, it is usually the 3:2 or the 5:2 resonances that act [2]. One of the main reasons to study the phenomenon is that a star can go from regular pulsations to chaos through a PD bifurcation cascade (known as a Feigenbaum cascade). Buchler et al. [2] proved that the characteristic light variations of RV Tauri stars, which show alternating deep and shallow minima, can be interpreted as a result of deterministic chaos of low dimension.

Even a Mira star, (R Cyg), was observed to show this phenomenon [6], and quite recently BL Herculis stars with PD were discovered in the OGLE-III data [14], confirming earlier theoretical predictions. RR Lyr stars, on the other hand, have been thought to pulsate quite regularly without low order resonances. This belief was based on decades-long observations and hydrodynamic models, with the only disturbing fact being the perplexing presence of amplitude and phase modulation (known as the Blazhko effect) in an increasing number of these stars. Therefore, the discovery of PD in the *Kepler* data was a surprise, forcing us to overhaul existing models and theories of RR Lyr pulsation.

2 Discovery of Period Doubling in RR Lyrae Stars

Kepler is a NASA Discovery mission to find Earth-like planets in the habitable zones of solar-like stars using the transit method [2]. It provides incredibly high-precision, quasi-continuous observations of a 115 deg^2 swath of the sky. The currently known sample of RR Lyr stars in the *Kepler* field consists of some 40 members, the majority of which are RRab stars, and half of which show Blazhko modulation. The field contains RR Lyrae itself, and despite of its brightness, hence heavy saturation on the CCD, we managed to get extremely precise photometry for this important target with *Kepler* [16].

We found PD in the first release of data for RR Lyrae itself (KIC 7198959) [7], then subsequently in two other *Kepler* Blazhko RR Lyr stars: V808 Cyg (Fig.1) and V355 Lyr (KIC 4484128 and KIC 7505345, respectively), both of which are much fainter than RR Lyrae itself [16]. The strength of the PD is variable; at the strongest phase the difference between subsequent maxima can be as large as 0.1 magnitude in RR Lyrae. We found that PD is stronger in certain Blazhko phases. There are hints in another four modulated stars of half-integer frequencies [16], which means that at least half of the modulated RRab stars show PD as well. After monitoring our RR Lyr star sample with *Kepler* for years we expect to see PD in more stars.

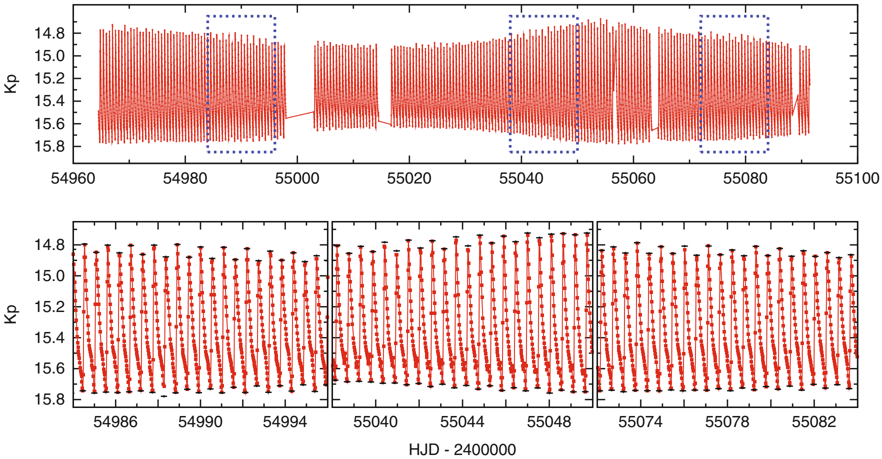

Fig. 1 *Top*: A *Kepler* light curve of the Blazhko star V808 Cygni (KIC 4484128) in quarters Q1 and Q2 showing 133 d of observations. Gaps in the data are due to safe mode events of the spacecraft and planned data download periods. The Blazhko cycle is around 90 d. *Bottom*: Magnification of three 12-d sections of the light curve highlighted by rectangles in the upper panel showing the characteristic period doubling behaviour. Polynomial fitting of the maxima and minima are also plotted for better visibility

Interestingly, non-Blazhko stars do not show PD down to the precision of the *Kepler* measurements [16], [12]. Despite close monitoring of RR Lyr stars it was not possible to detect PD previously, partly because consecutive cycles can rarely be observed from one geographical location, while the usually low amplitude of the phenomenon and its non-stationary nature also add to the difficulties.

3 Period Doubling and the Blazhko Effect

The PD phenomenon is intimately connected to the Blazhko cycle. Therefore by studying it, we may gain new insights into the intricacies of the Blazhko effect. Importantly, we succeeded in reproducing PD in hydrodynamic models [16], and unambiguously traced its cause back to a 9:2 resonance between the fundamental mode and the ninth overtone, which is a strange mode [8, 10].

Based on resonant amplitude equations accounting for the 9:2 resonance between the fundamental mode and the ninth (strange) overtone, Buchler and Kolláth [3] have found that this resonance may give rise not to only period doubled solutions, but irregularly (chaotic) modulated solutions as well. This is important, since recent observations show that the Blazhko effect is not a clockwork precision process: both long-term and cycle-to- cycle variations are frequently found in the modulation (see, e.g., [5]). Further investigations should clarify whether these amplitude equations can describe state-of-the-art hydrodynamic model calculations and, ultimately, real

RR Lyr stars. If that turns out to be the case, then this elegant prediction may be the long-sought explanation of the mysterious Blazhko effect. Additional complicating effects can also contribute to the whole picture, such as resonances involving nonradial modes [13], three-mode resonances [10] and magneto-hydrodynamic dynamo-like processes [15]. Beyond doubt, the discovery of period doubling in the *Kepler* data has opened a whole new avenue in RR Lyr star research.

Acknowledgements We gratefully acknowledge the entire *Kepler* team, whose outstanding efforts have made these results possible. This project has been supported by the 'Lendület' program, the Hungarian OTKA grants K83790 and MB08C 81013, the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 269194. R. Szabó was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

References

1. Borucki, W.J., Koch, D., Basri, G., Batalha, N., Brown, T., et al.: Kepler planet-detection mission: introduction and first results. Science **327**, 977–980 (2010)
2. Buchler, J.R., Kolláth, Z, Serre, T., Mattei, J.: Nonlinear analysis of the light curve of the variable star R Scuti. ApJ **462**, 489–501 (1996)
3. Buchler, J.R., Kolláth, Z.: On the blazhko effect in RR Lyrae stars. ApJ **731**, 24 (2011)
4. Buchler, J.R., Kovács, G.: Period doubling bifurcations and chaos in W Virginis models. ApJL **320**, L57–L62 (1987)
5. Guggenberger, E., Kolenberg, K., Chapellier, E., Poretti, E., Szabó, R., et al.: The CoRoT star 105288363: strong cycle-to-cycle changes of the Blazhko modulation. MNRAS **415**, 1577–1589 (2011)
6. Kiss, L.L., Szathmáry, K.: Period-doubling events in the light curve of R Cygni: evidence for chaotic behaviour. A&A **390**, 585–596 (2002)
7. Kolenberg, K., Szabó, R., Kurtz, D.W., Gilliland, R.L., Christensen-Dalsgaard, J., et al.: First Kepler results on RR Lyrae stars. ApJL **713**, L198–L203 (2010)
8. Kolláth, Z., Molnár, L., Szabó, R.: Period doubling bifurcation and high-order resonances in RR Lyrae hydrodynamical models. MNRAS **414**, 1111–1118 (2011)
9. Kovács, G., Buchler, J.R.: Regular and irregular nonlinear pulsation in population II Cepheid models. ApJ **334**, 971–994 (1988)
10. Molnár, L., Kolláth, Z., Szabó, R.: Uncovering hidden modes in RR Lyrae stars. These proceedings (2011)
11. Moskalik, P., Buchler, J.R.: Classical Cepheids with RV Tauri characteristics? ApJ **366**, 300–307 (1991)
12. Nemec, J.M., Smolec, R., Benkő, J.M., Moskalik, P., Kolenberg, K., et al.: Fourier analysis of non-Blazhko ab-type RR Lyrae stars observed with the Kepler space telescope. MNRAS **417**, 1022–1053 (2011)
13. Nowakowski, R.M., Dziembowski, W.A.: Resonant excitation of nonradial modes in RR Lyr stars. AcA **51**, 5–47 (2001)
14. Smolec, R., Soszynski, I., Moskalik, P., Udalski, A., Szymanski, M.K., et al.: Discovery of period doubling in BL Herculis stars of the OGLE survey. Observations and theoretical models. MNRAS **419**, 2407 (2012)
15. Stothers, R.B.: A new explanation of the Blazhko effect in RR Lyrae stars. ApJ **652**, 643–649 (2006)
16. Szabó, R., Kolláth, Z., Molnár, L., Kolenberg, K., Kurtz, D.W., et al.: Does Kepler unveil the mystery of the Blazhko effect? First detection of period doubling in Kepler Blazhko RR Lyrae stars. MNRAS **409**, 1244–1252 (2010)